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RESEARCH MEMORANDUM

PRELIMINARY INVESTIGATION OF THE EFFECTS OF INLET ASYMMETRY ON THE PERFORMANCE OF CONVERGING-DIVERGING DIFFUSERS AT TRANSONIC SPEEDS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The effects of inclining the plane of the inlet on the performance of several converging-diverging diffusers at zero angle of attack have been investigated at Mach numbers from 0.30 to 1.15 and at 1.41. It was found that converging-diverging diffusers designed for $M = 1.41$ with appreciable constant-area throat lengths operated without abrupt changes in performance over the entire speed and mass-flow ranges. It was also shown that spillage at slightly subcritical flow rates may be localized by inclining the plane of the inlet. At slightly subcritical flow rates a small reduction in pressure loss was obtained at the highest test speed, $M = 1.41$, by inclining the inlet plane 45°. At speeds up to $M = 1.15$ the inclined inlets had about the same pressure recovery as the unskewed inlets.

INTRODUCTION

At low supersonic Mach numbers, the efficiency of normal shock compression is relatively high; thus the simple open-nose or pitot-type inlet is frequently satisfactory. Efficiencies higher than that for the free-stream normal shock can be realized by reducing the Mach number at which the normal shock occurs. This fact has led to the development of the axially symmetric converging-diverging systems, reference 1. The efficiency of such systems is limited, first, by the requirement that they be self-starting, which places a maximum value upon the amount of supersonic compression which can be realized without the use of variable-area devices; and, second, by the requirement for axially symmetric systems that the flow at the center line be directed along the axis. The latter requirement demands a strong shock at stream Mach number over a region near the axis (ref. 2). Because the maximum contraction ratio

for which supersonic flow can be started increases with increasing Mach number, it is inherent that the compression to subsonic flow from a stream Mach number below the design starting Mach number occur through an external normal shock with resulting high drag.

In order to avoid the inherent difficulties of the simple convergent-divergent air induction system and the complication of mechanical systems for varying the contraction ratio in operation, an inlet with numerous holes in the converging section was designed and tested (ref. 3). If the entering flow rate was in excess of that which could pass through the minimum section, equilibrium was established by permitting the excess to return to the main stream, bypassing the throat section; thus detachment of the bow shock was avoided but in its place was established a sizeable region of small disturbances around the inlet caused by the rejected air.

If the plane of the inlet is tilted from the perpendicular, at slightly subcritical flow rates air will be spilled from the rearward part of the inlet only, thus allowing automatic adjustment of the flow rate as in the perforated inlet but confining disturbances to only a part of the inlet periphery. The second limitation inherent in the axially symmetrical converging inlets, that of shock reinforcement on the axis, is removed by tilting the inlet plane inasmuch as this asymmetry permits nonaxial flow directions and allows the supersonic compression to be distributed along the axis.

The purpose of the present preliminary investigation was to determine the pressure-recovery and flow-spillage characteristics of inclined convergent-divergent diffusers at transonic speeds. Two symmetrical and three inclined asymmetrical inlets, designed on the basis of one-dimensional theory for $M = 1.41$, have been tested at zero angle of attack over a Mach number range from 0.30 to 1.15 and at 1.41; the corresponding range of Reynolds number was 250,000 to 600,000 based on inlet diameter. The performance of these inlets is presented in the form of schlieren photographs of the flow at the inlet lips together with pressure-recovery measurements over a range of flow rates at several stream Mach numbers.

SYMBOLS

a	speed of sound, ft/sec
H	total pressure, lb/sq ft
ΔH	volume-weighted, integrated average total-pressure loss, lb/sq ft

M	Mach number, V/a
V	velocity, ft/sec
p	static pressure, lb/sq ft
m	mass flow, slugs/sec
m_0	mass flow in free-stream tube of area equal to capture area

Subscripts:

0	free stream
2	at diffuser measuring station

APPARATUS AND METHODS

Two types of tunnel were employed for the generation of the test Mach numbers. One was a conventional Laval nozzle, 8.1 by 8.9 inches at the test section, designed for M = 1.41. The other was a transonic tunnel 4.5 inches high by 6.25 inches wide with slotted walls both above and below the model. The transonic slotted tunnel provided continuous operation through the speed range from zero up to Mach number 1.15; with an empty test section the maximum Mach number variations were less than ±0.007 across the area occupied by the inlet. Mach number adjustment in the slotted tunnel was provided at subsonic speeds by varying stream stagnation pressure to a maximum of 150 centimeters of mercury, absolute, and at supersonic speeds (maximum stagnation pressure) by withdrawing air from the tunnel, thus effectively changing the throat-to test-section-area ratio. The slots served the added purpose of providing a choke-free test section allowing continuous tunnel operation throughout the range of Mach number and back pressure tested. The results of previous investigations conducted in this transonic test section, of a 10-percent-thick symmetrical wedge the cross-sectional area of which was 40 percent greater than that of the inlet investigated herein, showed excellent agreement of chordwise-pressure distribution with theory and the results of other experiments throughout the test Mach number range to 1.18. Although these two-dimensional results are not directly applicable to the three-dimensional inlet presently discussed, they indicate that, for the purposes of the present investigation, the transonic tunnel may be considered free of boundary interference effects.

The various inlets tested are identified in table I. All inlets had a basic diameter of 1.5 inches with a conical convergence,

40 included angle, to a 1.45-inch-diameter throat (fig. 1). The resulting throat area was 0.935 times the inlet area, a contraction ratio which, theoretically (ref. 1), should allow the inlet to start at M = 1.41. Behind the constant-diameter throat was a conical subsonic diffuser which had an included angle of approximately 5° and expanded to an area equal to twice that of the throat. Representative photographs of the models mounted in the Mach number 1.41 tunnel are shown as figure 2.

The back pressure in the diffuser, and hence the rate of flow, was controlled by an adjustable plug at the end of a straight section behind the diffuser. Visualization of the flow was accomplished by means of a conventional double-parabolic-mirror single-pass schlieren system and photographs were made using a high-voltage discharge through a General Electric B-H6 mercury lamp; this lamp also permitted continuous visual observation. A rake of nine total-pressure and two static-pressure tubes (fig. 1) together with three surface-pressure tubes was installed at the end of the subsonic diffuser. The rake was mounted on a sting that could be rotated to cover the entire exit of the diffuser.

The rake total pressures were read to an accuracy of ±0.2 millimeter of mercury; all other pressures were read to an accuracy of ±1 millimeter of mercury. The accuracy of the data points, as plotted, has been maintained with maximum probable errors as follows:

Mach number, M	±0.004
Back-pressure ratio, p_2/H_0	±0.003
Mass-flow ratio, m_2/m_0	±0.02
Static-pressure rise, Δ_p/H_0	±0.006
Total-pressure loss, $\Delta H/H_0$	±0.001
Total-pressure ratio, H/H_0	±0.002

The above probable errors include errors of integration for m_2 and for ΔH. The mass flow was obtained by integration of the local values of mass flow at the diffuser measuring station and ΔH was weighted against volume flow.

RESULTS AND DISCUSSION

Schlieren observations.- Schlieren photographs of the flow at the inlet of several converging-diverging diffusers are shown as figure 3. In these pictures, regions of increasing pressure (density) appear as light areas or lines; conversely, regions of decreasing pressure (density) appear darkened.

For the short, axially symmetric inlet, configuration I, the initial shock with minimum back pressure is attached to the inlet lips at

M = 1.41. Theoretically, at this Mach number, increasing the back pressure should cause no change in the external flow until a p_2/H_0 value of 0.93 is reached. Above that point, the normal shock in the throat would be expected to jump forward of the inlet abruptly becoming a detached bow wave. Then, theoretically, in order to restart the inlet the back pressure would have to be lowered again to the value of $0.89H_0$, thus effecting a hysteresis in the detached to attached condition. In practice, however, no abrupt change in shock position was observed; this fact, in accord with numerous other experiments, probably results from progressive changes in the effective minimum area which accompany boundary-layer changes in the diffuser. The presence of appreciable constant-area throat lengths in these inlets may also contribute to the lack of any discontinuity in performance. Increasing the back pressure resulted in increased spillage ahead of the inlet and reaccelerated the flow to supersonic Mach numbers over the inlet lips. This reacceleration was followed by a shock the intensity of which increased as the back pressure was increased.

For the 5° and 10° skewed configurations, schlieren photographs indicate that, with increasing back pressure, air was first spilled over the most rearward part of the lip and then rapidly around the lip until it occurred over the entire periphery of the inlet. This condition is shown by movement of the detached wave which first occurs at the rearmost part of the lip (see configuration III, fig. 3(a)); whereas an oblique wave remains attached to the forwardmost part of the inlet lip; with increasing back pressure the detached wave moves forward to a position ahead of the entire lip. No abrupt changes in shock pattern were observed with variations in back pressure.

Increasing the angle of skew to 45° placed the inlet lips behind the wave emanating from the inner surface of the forwardmost part of the lip; in this configuration it was necessary to increase the length of the constant-diameter throat to maintain the same cross-section area used in configurations I, II, and III. The new throat was made 2 inches longer than the original one. Schlieren pictures of the flow about the axially symmetric inlet with the long throat, configuration IV, are similar to those of configuration I and show the increasing intensity of the expansion over the lip and subsequent shock as mass-flow ratio is reduced and the detached wave is moved forward. It is again noted that spillage affects the entire periphery of the inlet. Spillage effects at M = 1.41 were clearly visible at a back-pressure ratio near 0.88. For a skew angle of 45° (fig. 3(a)), the shock at M = 1.41 appeared attached to the forward lip throughout most of the range of back pressure; whereas an examination of the rearward parts of the lip at increasing back pressure shows a continuous forward movement of the bow wave indicating increasing spillage. As the back pressure is further increased, the secondary shock disappears and on the lower part of the

inlet is replaced by a region of turbulent subsonic flow. At these very high back pressures, such an inlet would have mixed flow regions on its sides but still maintain supersonic flow downstream of the forwardmost section of the lip.

At supersonic Mach numbers less than 1.41, the characteristic normal bow shock appeared ahead of the 0°, 5°, and 10° inlets. For the 45° skewed configuration which is shown in figure 3(b), the bow shock approaches the lip very closely at low back pressures, moving forward with increasing back pressure but indicating extensive spillage from the forwardmost part of the lip at extreme high back pressures only. Most of the spillage occurs from the rearward part of the lip as indicated by overexpansion and shock waves in the external flow. The appearance of appreciable thickness in the detached bow shock results from light deflection across the curved shock, the forward part of which is directly ahead of the inlet; the downstream edge corresponds to the intersection of the bow shock with the tunnel side walls. In cases where two apparent shock-wall intersections are observed, the phenomenon is ascribed to unequal spillage from the sides of the inlet resulting in a longitudinal displacement of the shock-wall intersection on the two side walls. The results of schlieren observation of the flow indicate that some local improvement in the external flow at less than critical flow ratios may be had by skewing the inlet, but large skew angles would be necessary to realize an improvement over a very wide range of mass-flow ratios.

At subcritical flow rates and Mach numbers below the design value, a skewed inlet such as this on an underslung nacelle might be effective in reducing turbulent flow past a wing inasmuch as the turbulent wake from spillage passing underneath the nacelle would allow a practically undisturbed stream to flow over the wing itself. In addition, the skewed inlets would be expected to provide improvement in pressure recovery at angles of attack greater than zero. It should also be noted that the projected frontal area will increase with angle of attack; this results in a corresponding increase in air flow.

Static-pressure recovery.- The static-pressure recovery, defined as the increase in static pressure from the free stream to the diffuser exit divided by the free-stream total pressure is presented in figure 4 for each of the five inlets tested. Plotted as a function of the mass-flow ratio m_2/m_0 the static-pressure rise, calculated from one-dimensional theory, decreases steadily to a limiting value of m_2/m_0. At the design Mach number, $M = 1.41$, the value of $\Delta p/H_0$ for the short inlets decreases at a slightly higher rate than the calculated curve; however, the recovery obtained experimentally was at all points within 0.03 of the calculated curve. A comparison of the experimental data shows that increasing the angle of skew had little effect on the static-pressure recovery at the design Mach number. With decreasing

stream Mach number a reduction in static-pressure recovery corresponding to the decrease in available free-stream dynamic pressure was observed (fig. 4). With decreasing Mach number, a variation in the limiting value of m_2/m_0 was also observed. This latter change results from the fact that the ratio of throat area to inlet area was fixed at 0.935, which permits a maximum subsonic entrance Mach number of 0.74, this being the Mach number behind a normal shock at the design condition. In a stream approaching the inlet at $0.74 < M < 1.41$, the stream-tube area is limited by choking at the throat to a value less than the capture area of the inlet $\left(\frac{m_2}{m_0} < 1.0\right)$. At lower subsonic speeds, $M < 0.74$, a stream tube the area of which is greater than the area of the inlet may be taken into the system and m_2/m_0 may exceed unity. At Mach numbers less than 1.41, the deviation of experimental data from corresponding theoretical curves shows no measurable advantage for either the skewed or unskewed configurations. The static-pressure recovery of all these inlets is presented in greater detail for more Mach numbers in figure 5.

A comparison of the data from the axially symmetric inlets with one-dimensional theory at the design Mach number shows a substantially higher recovery with the long inlet at flow rates m_2/m_0 just below unity. At lower Mach numbers, differences are not well defined and no apparent advantage holds for either configuration.

Total-pressure loss.- The total-pressure loss at the design Mach number is shown for each inlet as a function of mass-flow ratio m_2/m_0 in figure 6. Curves for the short inlets (fig. 6(a)) show a slightly detrimental effect of small angles of skew over the entire range of subcritical flow rates. At the highest skew angle, 45° (fig. 6(b)), the loss at values of m_2/m_0 slightly below unity was lower than for the straight inlet; at $\frac{m_2}{m_0} \leqq 0.7$, higher losses were incurred with the modified inlet. Although the improvement effected by the skewed inlet is small, it is significant that it occurs in a mass-flow range which might be encountered in normal operations. It is also significant that the gain, $\Delta H/H_0 \approx 0.004$, has been effected in a region where shock losses are small; the reduction in loss is of the order of 10 percent of the loss in an axially symmetrical system.

A comparison of the experimental data from tests of the short and long axially symmetric inlets (fig. 6) shows appreciable reduction in loss at mass-flow ratios just below unity as a result of increasing the length of the throat section.

The data presented in figure 6 are replotted in figure 7 as a function of the static pressure in the diffuser exit. This type of plot has the advantage of spreading the curves in the region of supersonic entry flow ($m_2/m_0 = 1.0$). In this range the 5° and 10° inlets show somewhat lower losses than the corresponding 0° inlet (fig. 7(a)); the 45° inlet, however, proved little different from the long symmetrical inlet. In this flow range, increasing supersonic Mach numbers are encountered in the diverging section resulting in higher compression losses as the back pressure is reduced. With the short throat, asymmetry of shock pattern is preserved in the diverging section of the skewed configurations and the intensity of the shocks is apparently less than that required by conditions of axial symmetry. In the long throat the flow may be returned to axial symmetry, thus the losses in the 0° and 45° long diffusers are approximately equal. On the basis of this scant evidence optimum design would appear to combine a short throat with the highest angle of skew consistent with maintaining attached flow all around the inlet lips. The advantages of such an inlet would be expected to increase with stream Mach number.

Pressure-loss characteristics of these inlets at Mach numbers from 0.30 to 1.15 and at 1.41 are presented in greater detail in figure 8. All the inlets tested operated without discontinuities in performance throughout the Mach number range. A comparison of the relative performance of the various inlets at transonic Mach numbers shows no marked differences.

Total-pressure distributions.- Typical exit total-pressure distributions along the vertical diameter are presented in figure 9. These distributions are very nearly symmetrical about the diffuser axis for the short unskewed inlet and are only slightly less uniform for the 45° inlet at the higher back pressures. At $M = 1.41$ with low back pressures, however, the distributions show regions of heavily retarded flow along the walls with some asymmetry in flow pattern. These regions of low-velocity air act to reduce the effective area of the diffuser resulting in the observed difference in the experimental and theoretical curves of $\Delta H/H_0$ plotted against p_2/H_0.

CONCLUSIONS

From the results of this preliminary investigation of the performance of axially symmetric and skewed converging-diverging diffusers at Mach numbers from 0.30 to 1.15 and at 1.41, it is concluded that:

(1) All the inlets operated throughout the transonic range without abrupt changes in performance. In this connection it should

be noted that the configurations tested had appreciable constant-area throat lengths.

(2) At slightly subcritical flow rates detachment of the bow shock and spillage was confined to the rearward part of the inlet periphery by inclining the entrance plane.

(3) At a Mach number of 1.41 and mass-flow ratios slightly less than unity, the loss in stagnation pressure in a long inlet with 45° skew was slightly ($0.004H_0$) less than that of the corresponding axially symmetric inlet; this small gain represents a 10-percent reduction in the total diffuser loss.

(4) The velocity distribution at the diffuser exit was not radically changed by skewing of the inlet.

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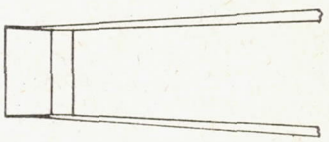
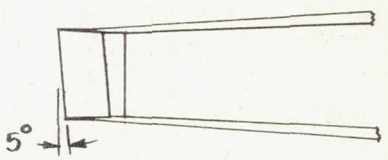
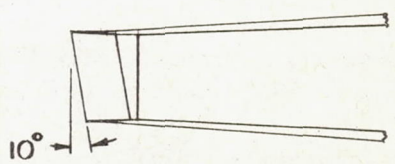
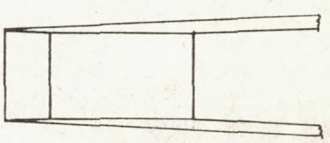
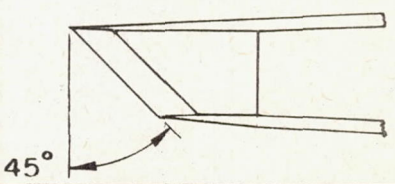
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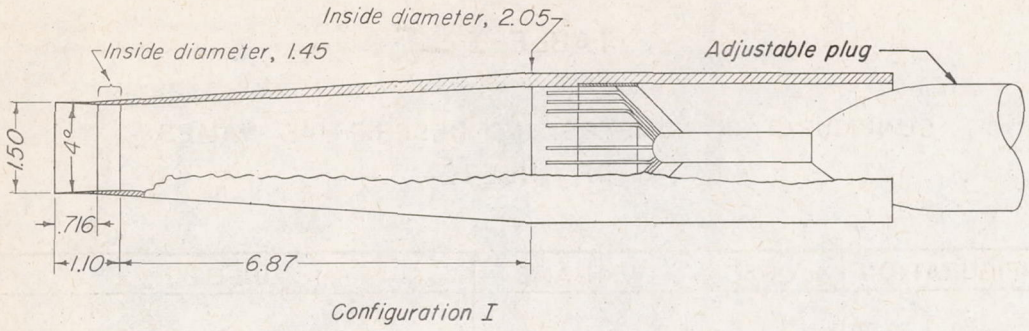
3. Evvard, John C., and Blakey, John W.: The Use of Perforated Inlets for Efficient Supersonic Diffusion (Revised). NACA RM E51B10, 1951.

TABLE I

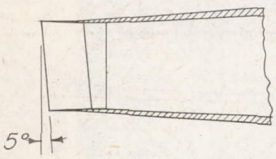
CONFIGURATION NUMBERS AND DESCRIPTIVE NAMES OF INLETS

CONFIGURATION	DESCRIPTIVE NAME	INLET
I	SHORT THROAT SYMMETRICAL INLET	
II	SHORT THROAT INLET, 5° SKEW	
III	SHORT THROAT INLET, 10° SKEW	
IV	LONG THROAT SYMMETRICAL INLET	
V	LONG THROAT INLET, 45° SKEW	

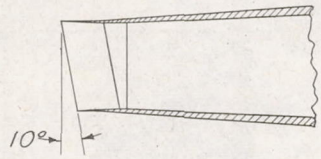
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Configuration I

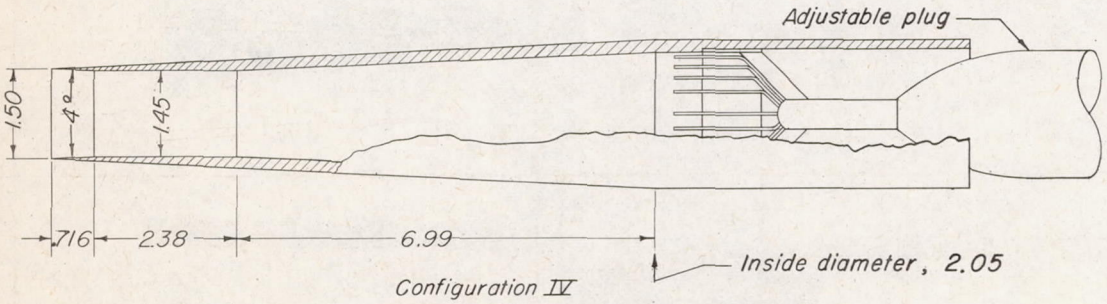


Configuration II

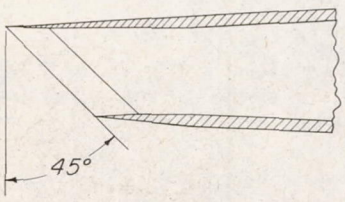


Configuration III

(a) Short inlets.



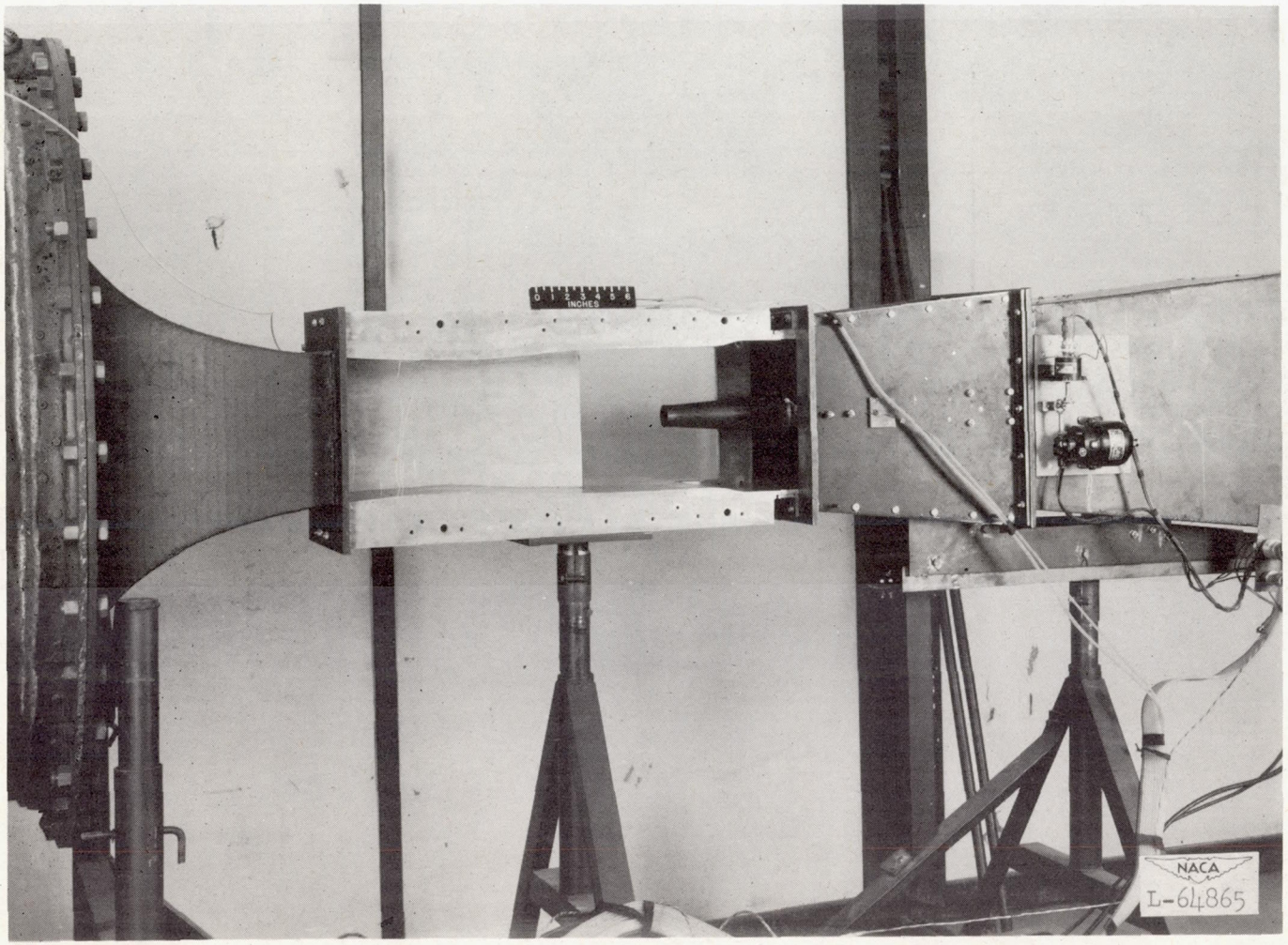
Configuration IV



Configuration V

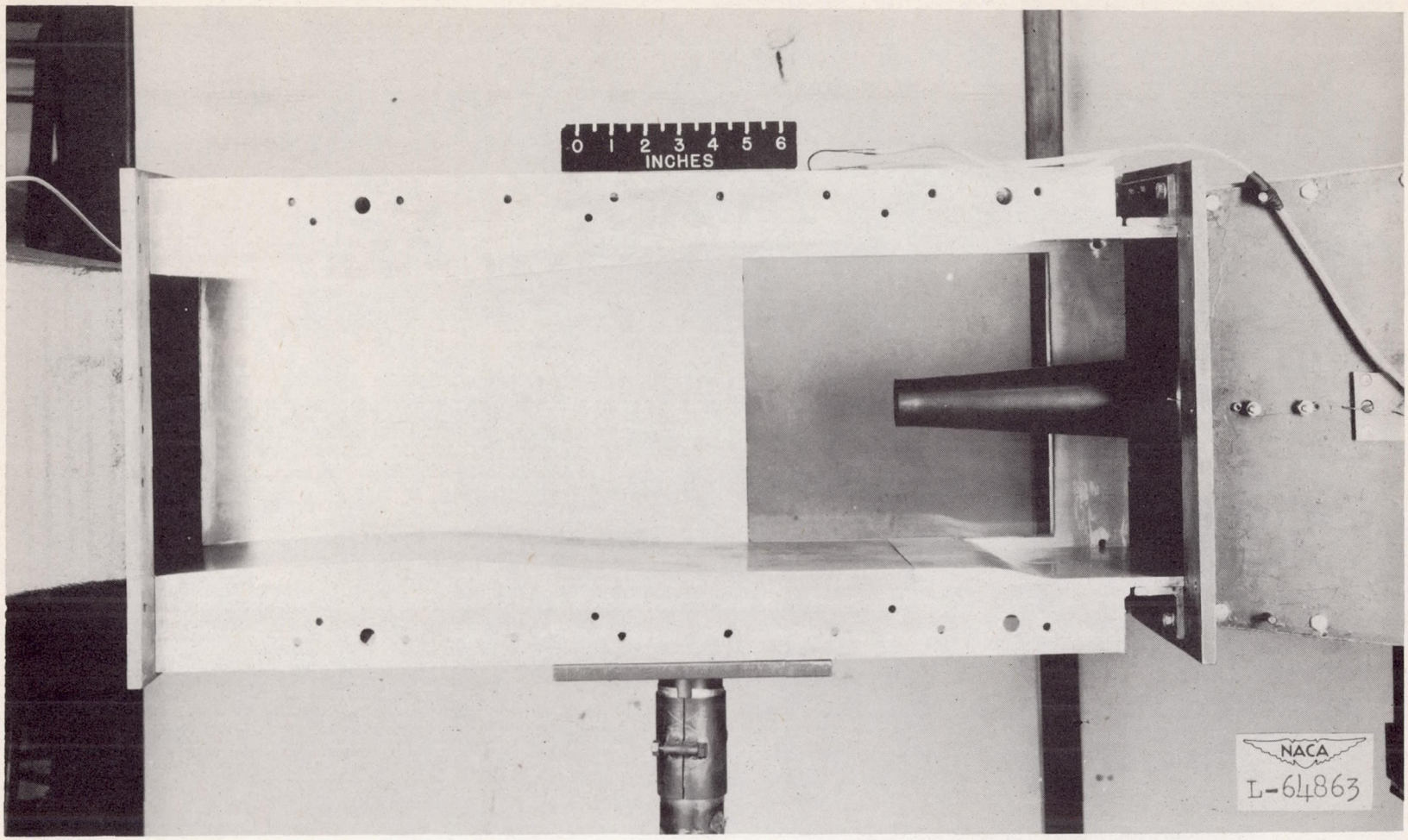
(b) Long inlets.

Figure 1.- General arrangement and principal dimensions of inlets.



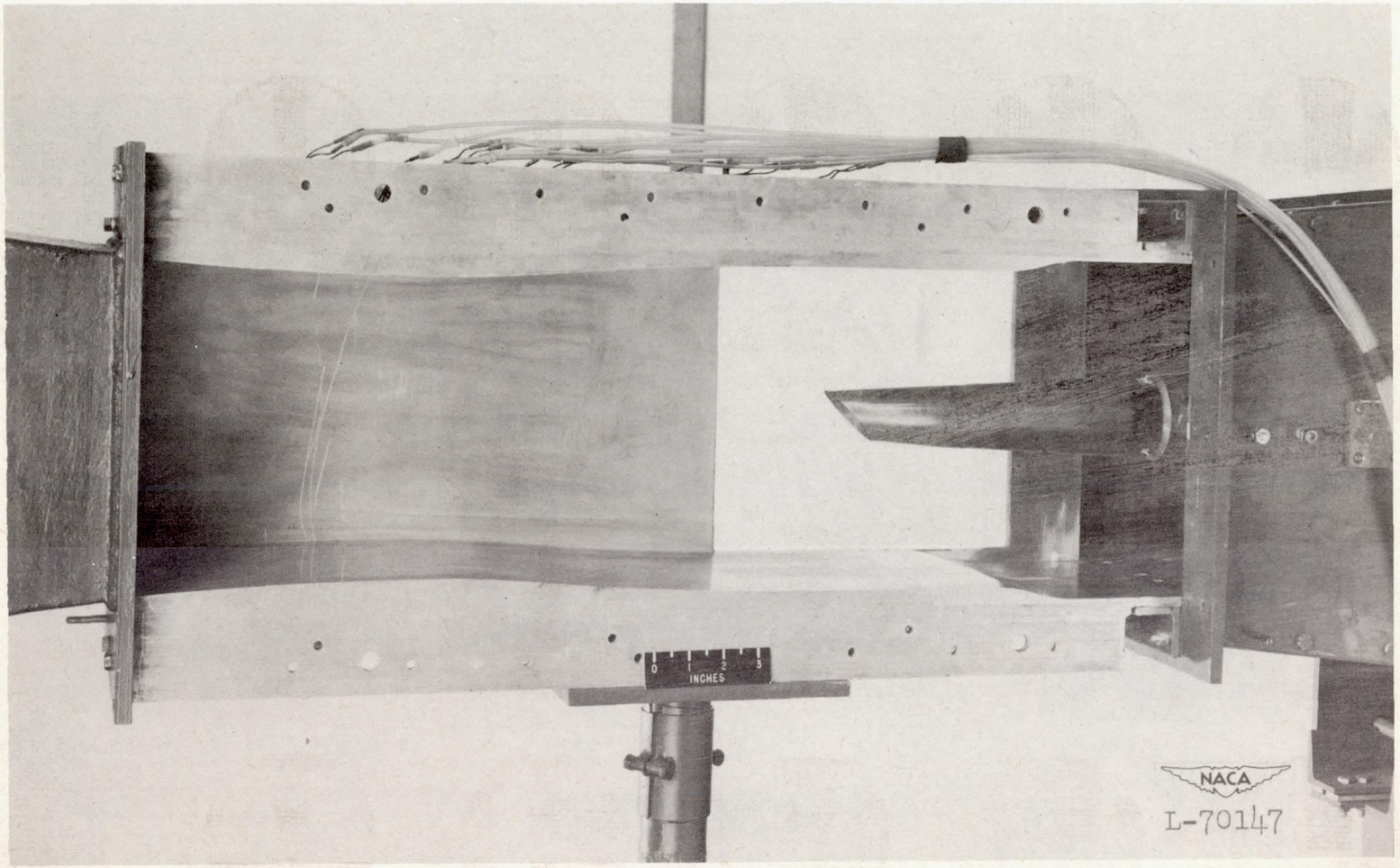
(a) Short symmetrical inlet.

Figure 2.- Representative views of model mounted in Mach number 1.41 tunnel.



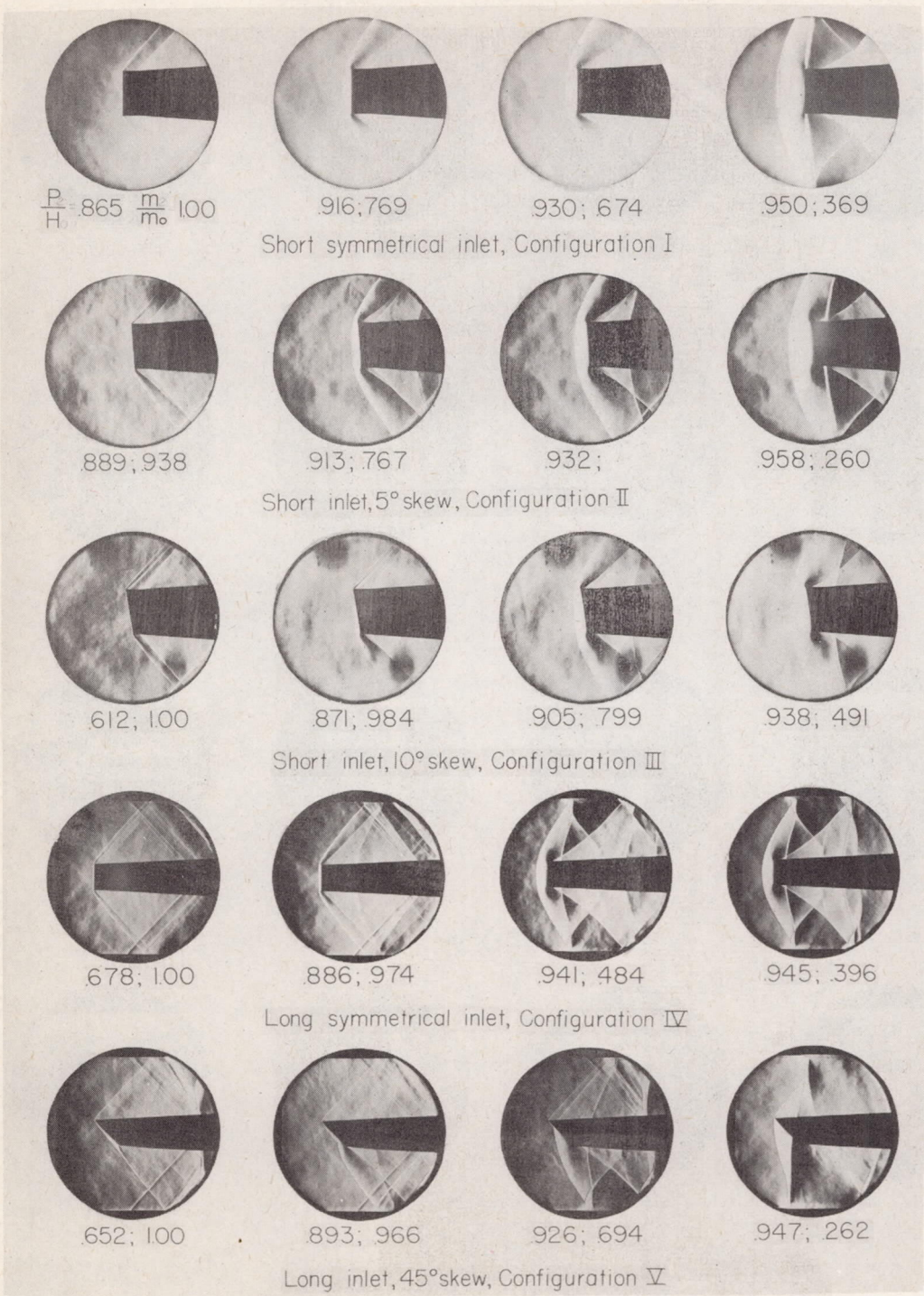
(b) Detailed view, short symmetrical inlet.

Figure 2.- Continued.



(c) Detailed view, long inlet, 45° skew.

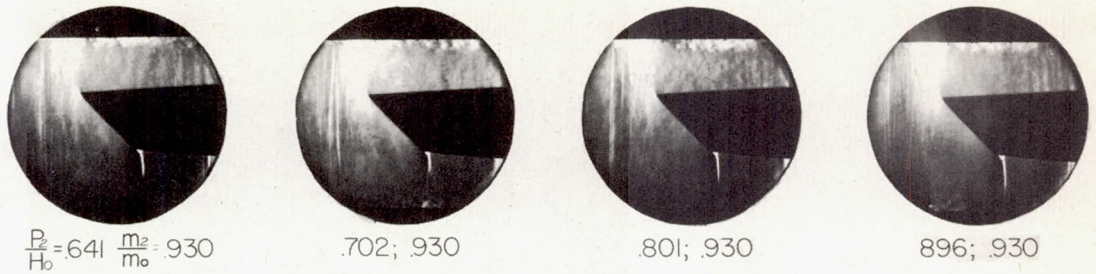
Figure 2.- Concluded.



(a) M = 1.41.

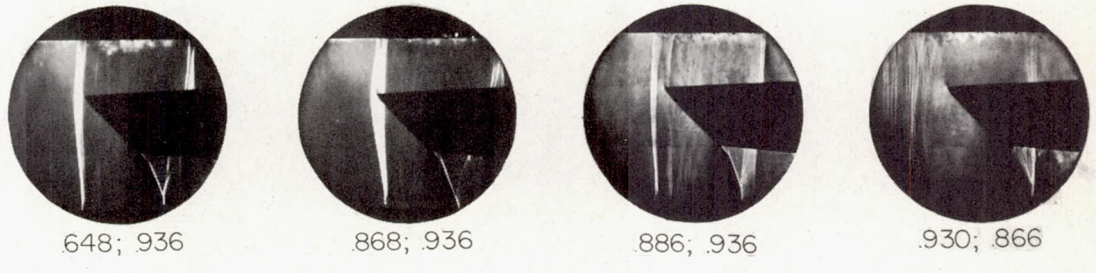
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Figure 3.- Schlieren photographs of the external flow in the vicinity of the inlet.



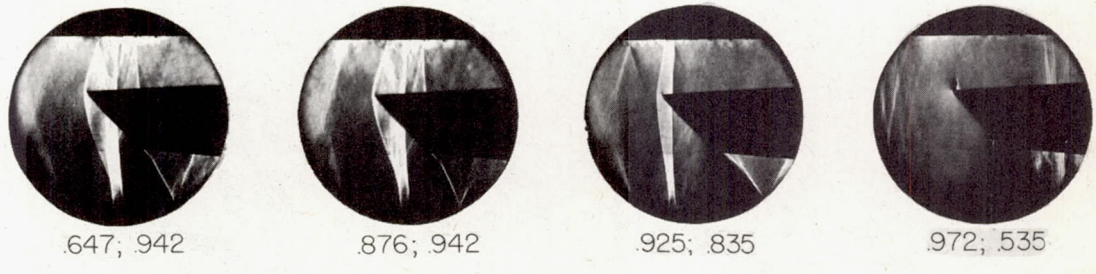
$\frac{P_2}{H_0}$=.641 $\frac{m_2}{m_0}$=.930 .702; .930 .801; .930 .896; .930

M=1.00



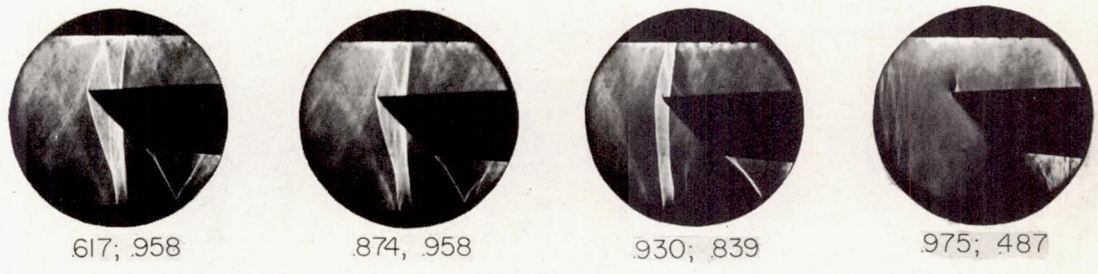
.648; .936 .868; .936 .886; .936 .930; .866

M=1.06



.647; .942 .876; .942 .925; .835 .972; .535

M=1.10



.617; .958 .874, .958 .930; .839 .975; .487

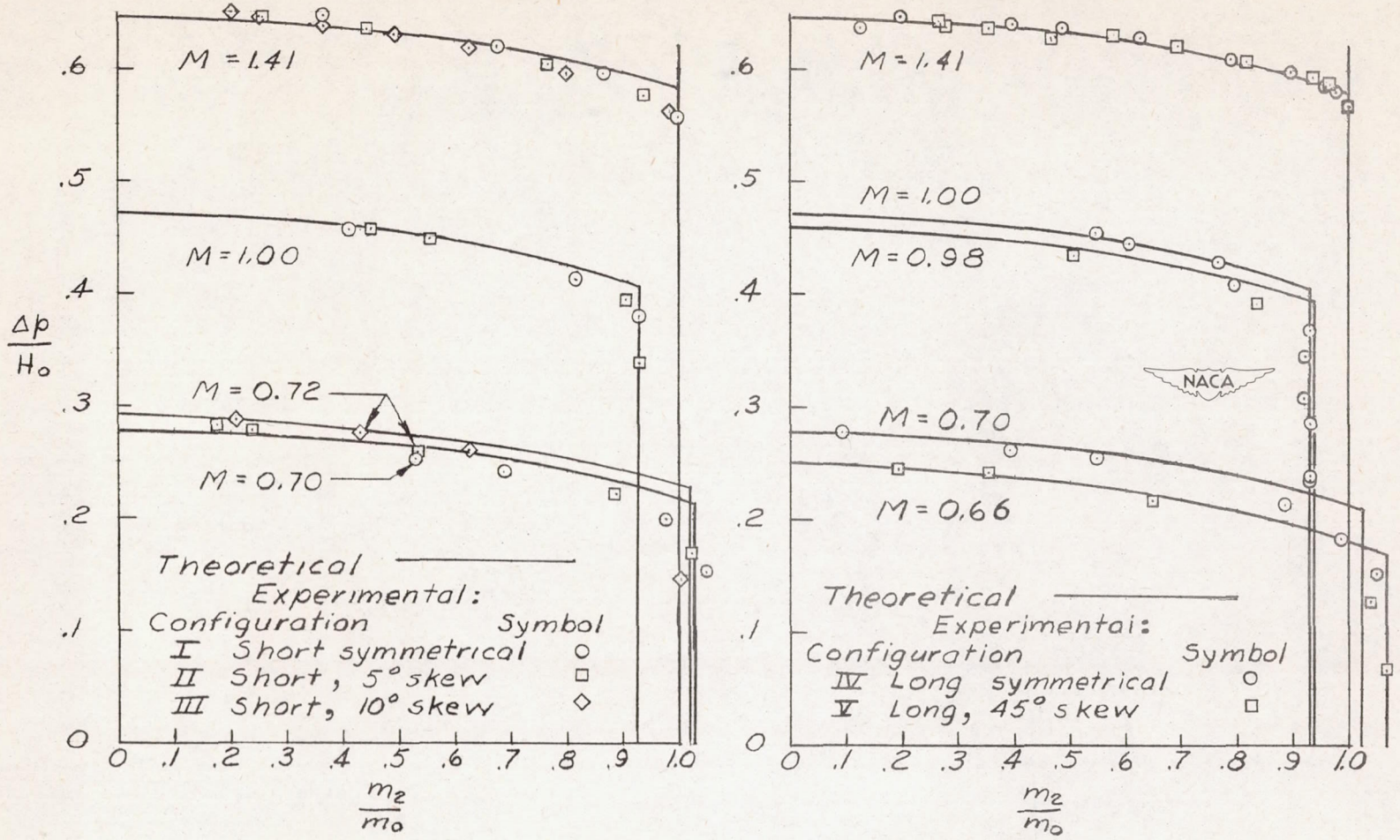
M=1.16

Long inlet 45° skew, Configuration V

(b) $1.0 < M_0 < 1.4$.

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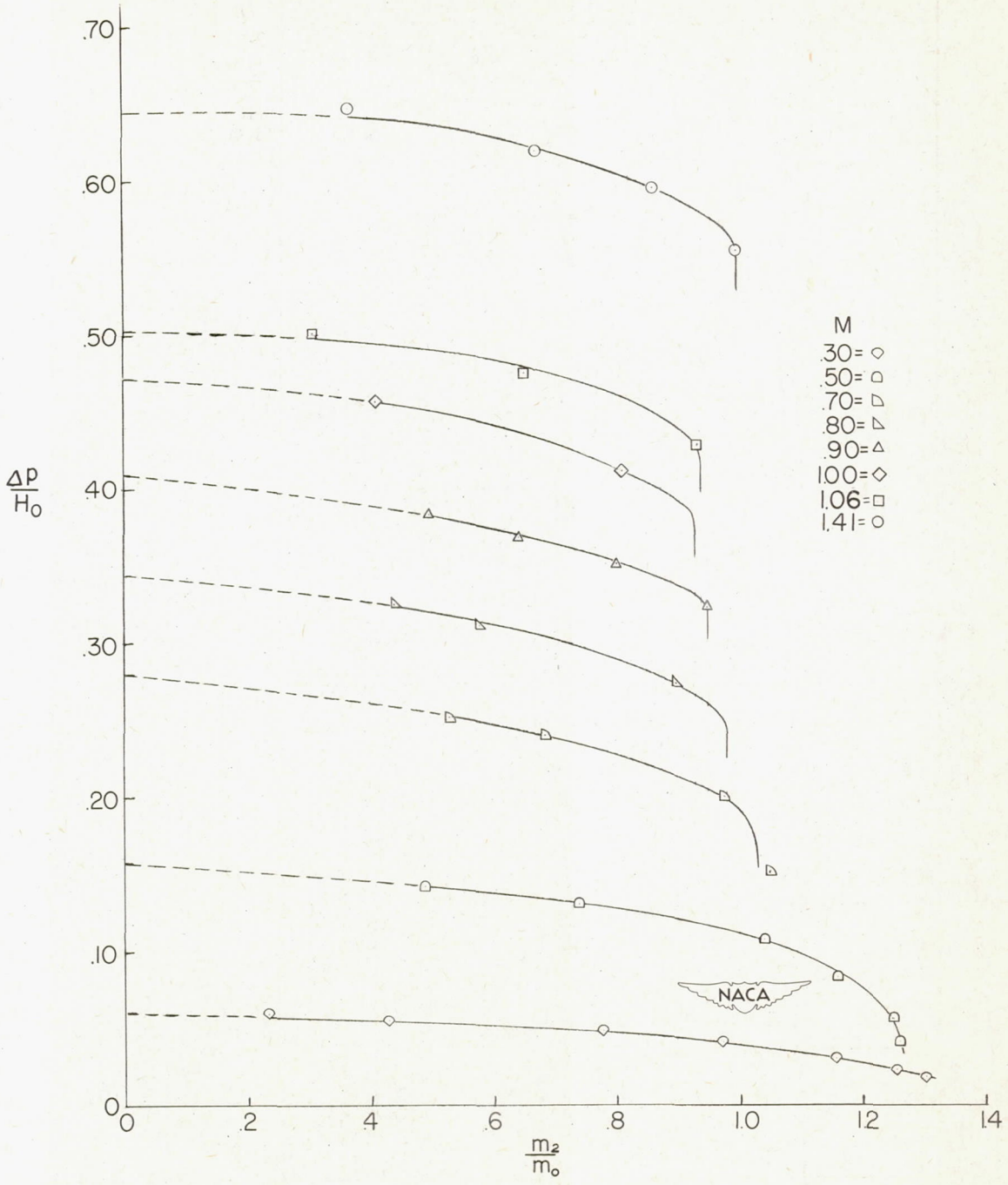
Figure 3.- Concluded.



(a) Short inlets.

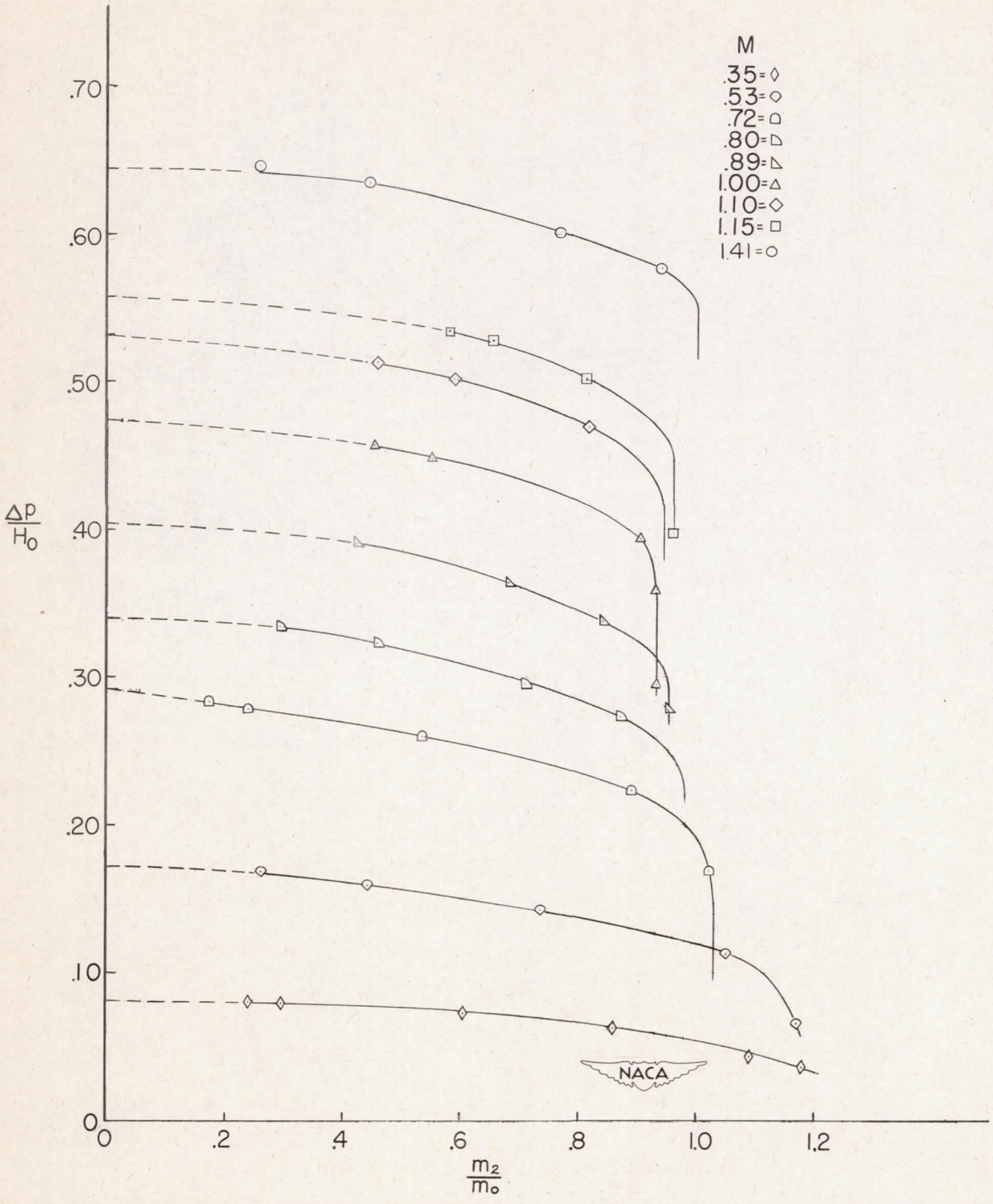
(b) Long inlets.

Figure 4.- Comparison of variation of static-pressure rise with mass-flow ratio for several values of Mach number.



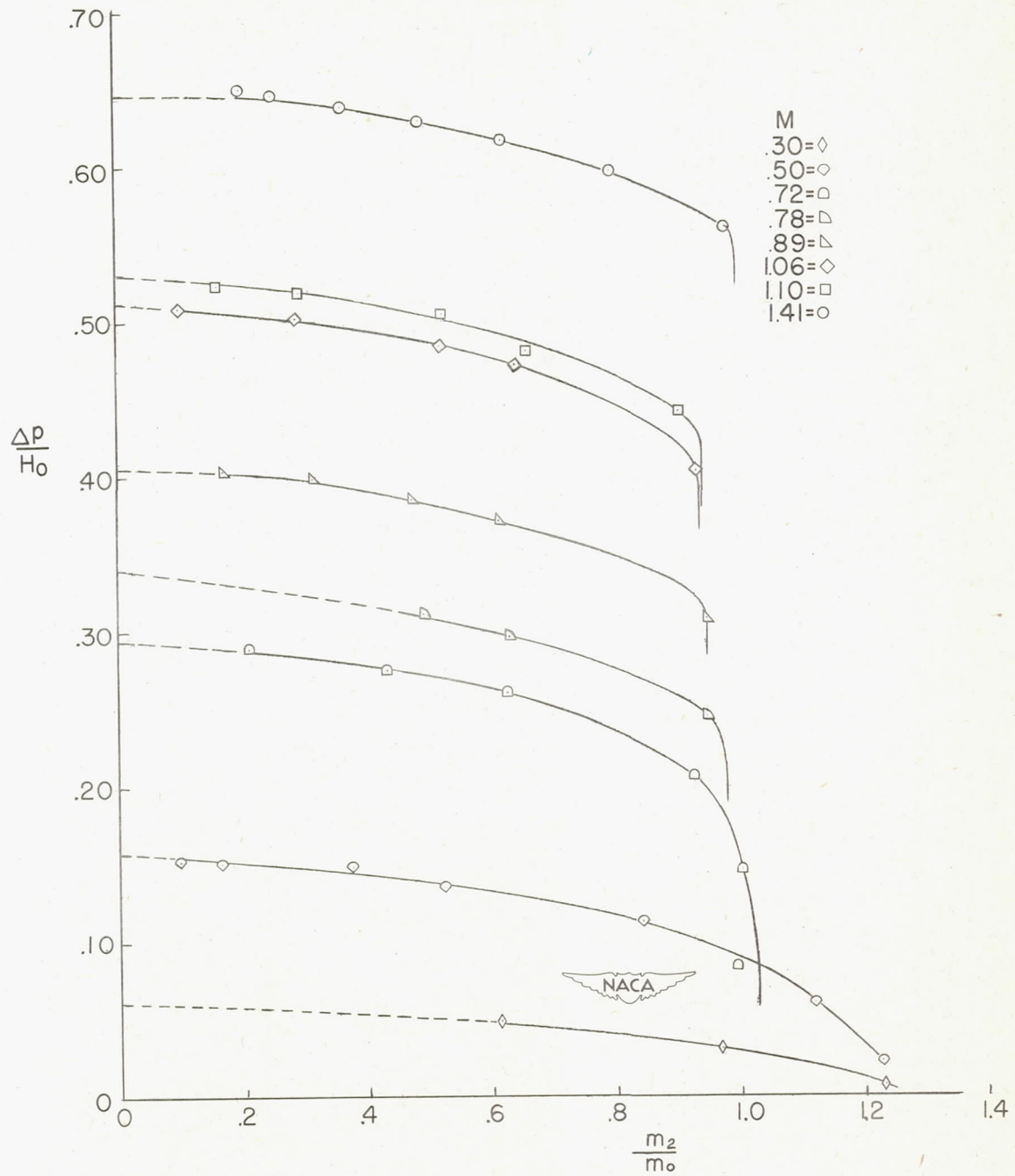
(a) Configuration I: Short symmetrical inlet.

Figure 5.- Variation of static-pressure rise with mass-flow ratio.



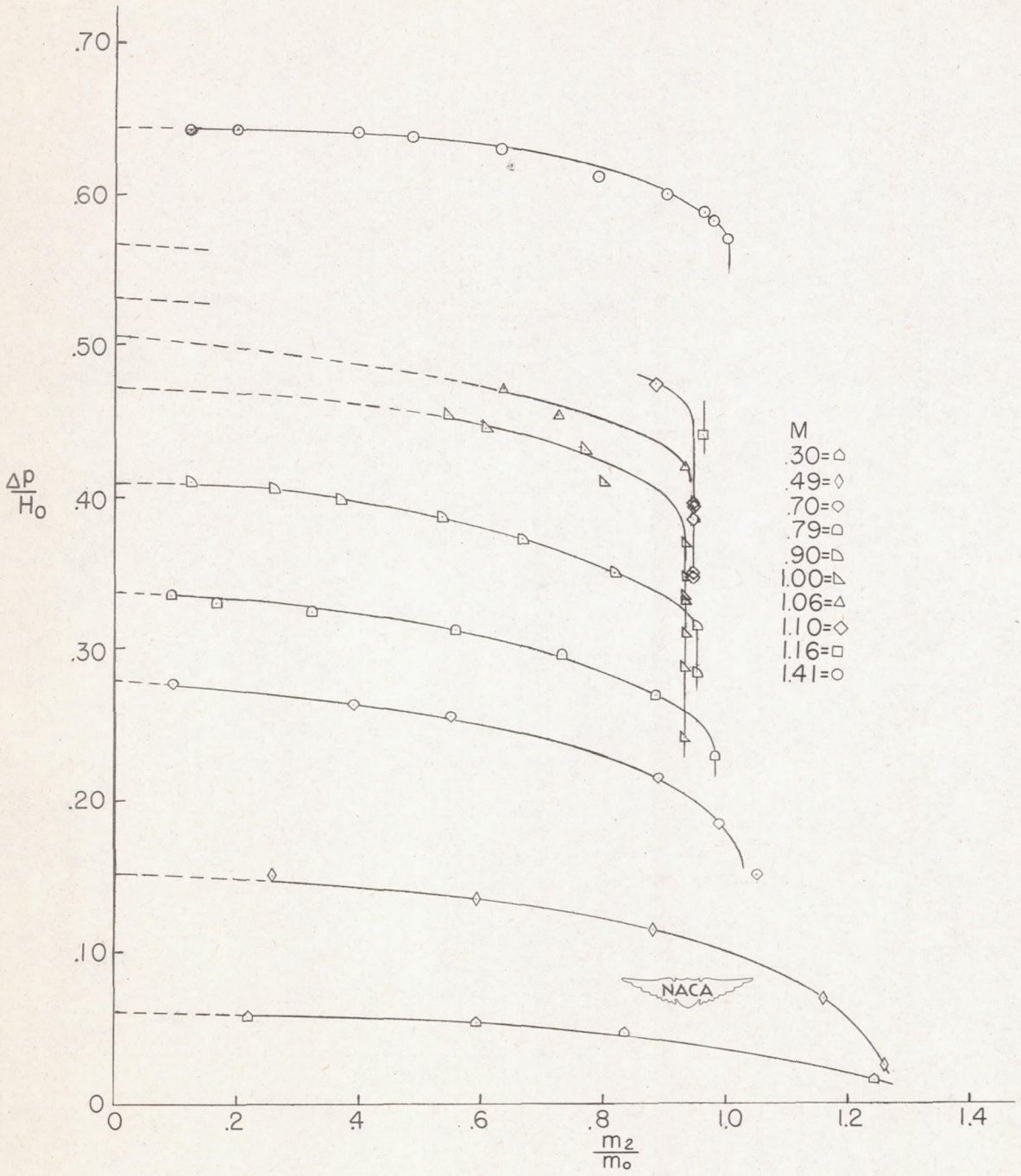
(b) Configuration II: Short inlet, 5° skew.

Figure 5.- Continued.



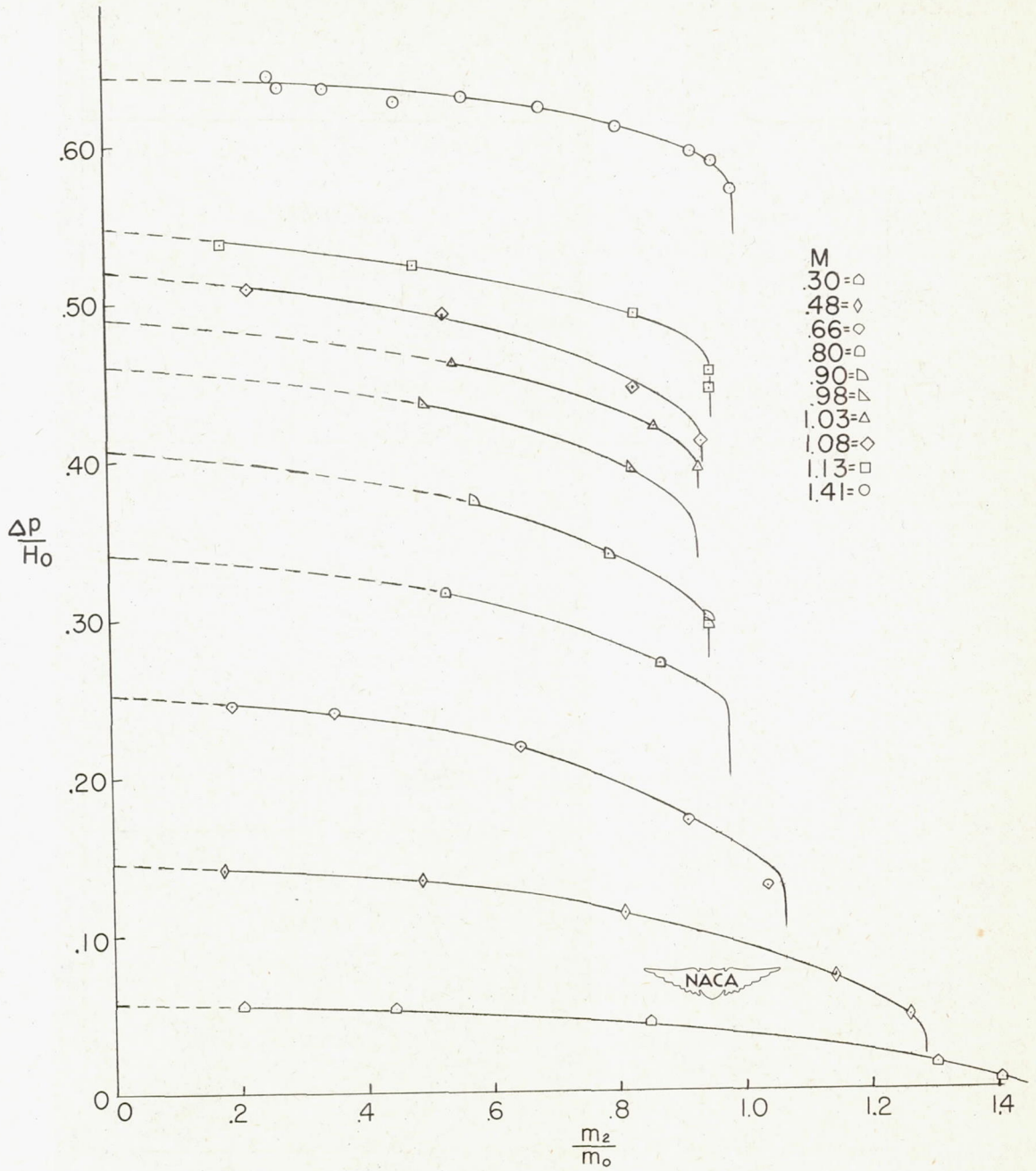
(c) Configuration III: Short inlet, 10° skew.

Figure 5.- Continued.



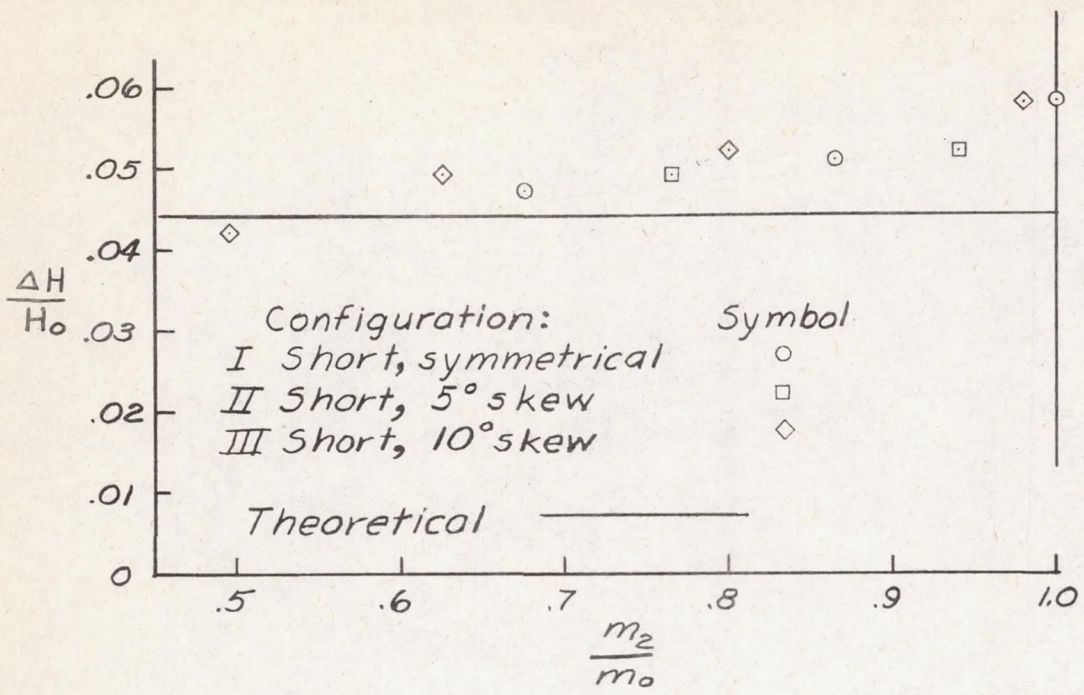
(d) Configuration IV: Long symmetrical inlet.

Figure 5.- Continued.

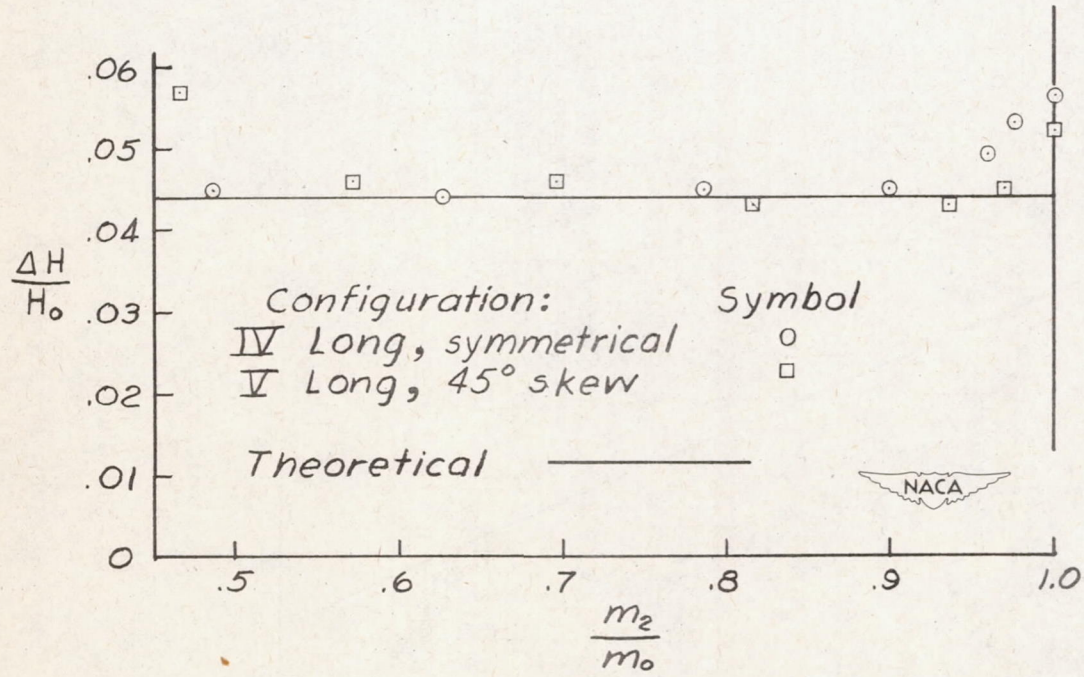


(e) Configuration V: Long inlet, 45° skew.

Figure 5.- Concluded.

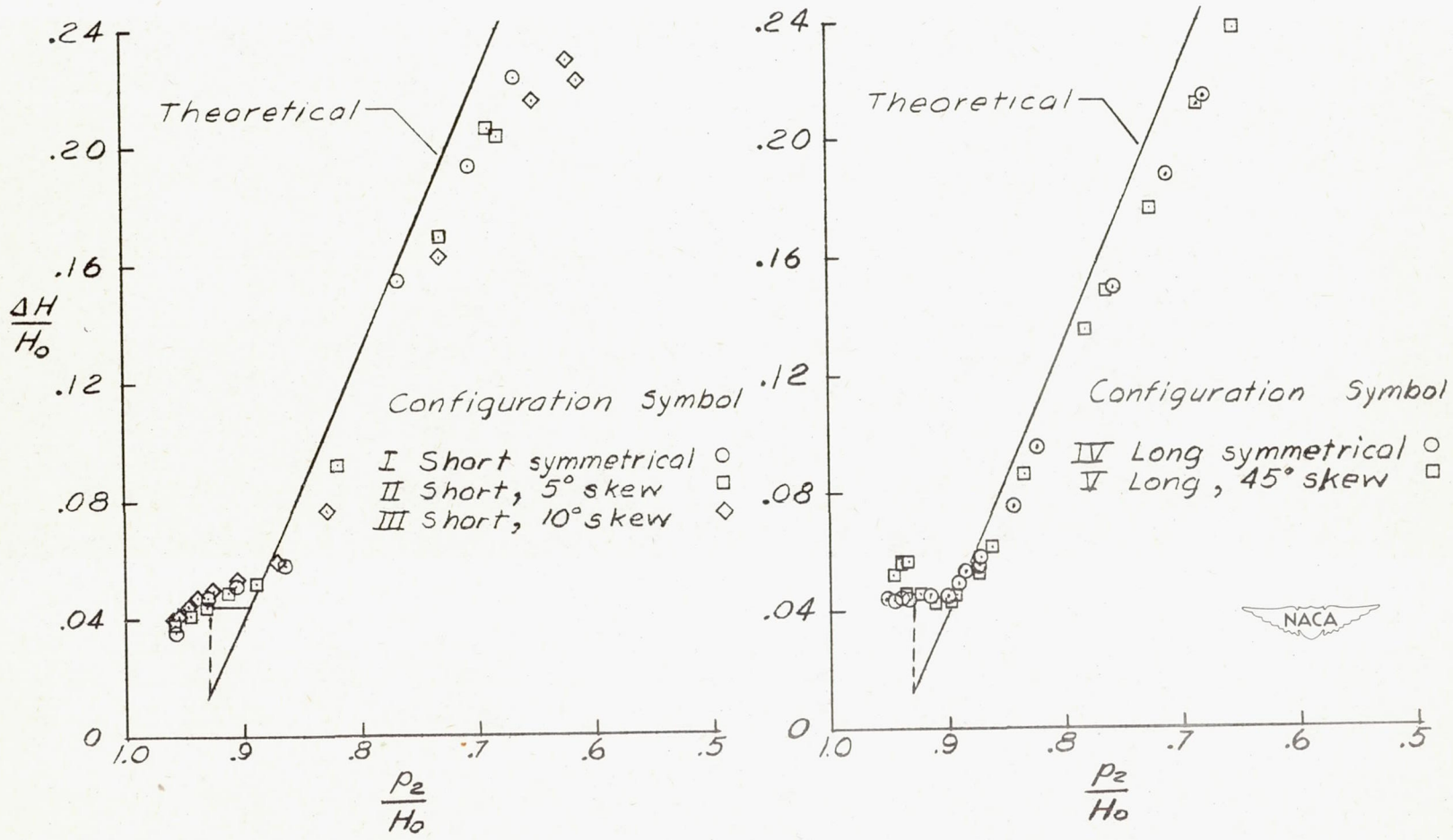


(a) Short inlets.



(b) Long inlets.

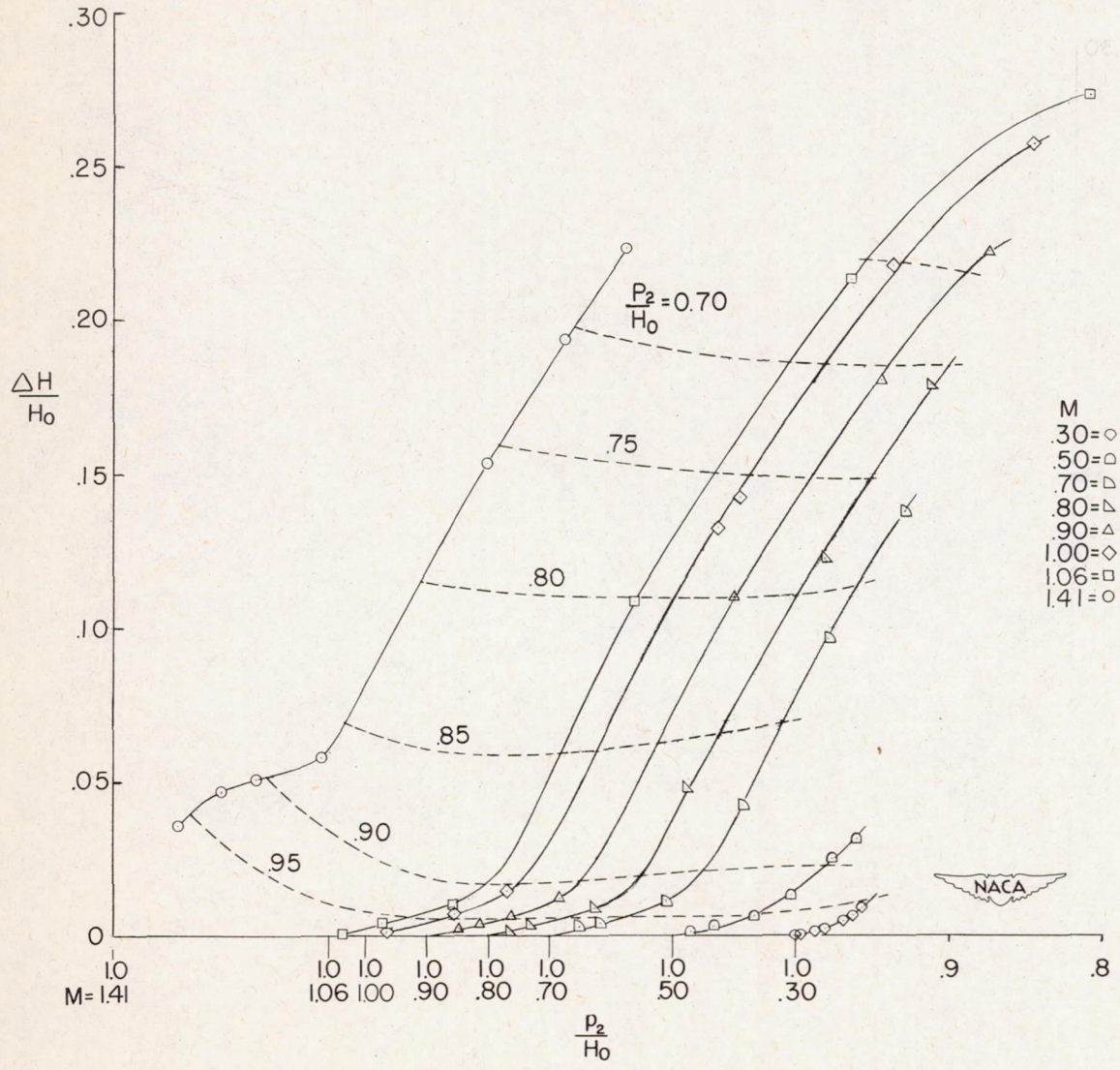
Figure 6.- Variation of total-pressure loss with mass-flow ratio at M = 1.41.



(a) Short inlets.

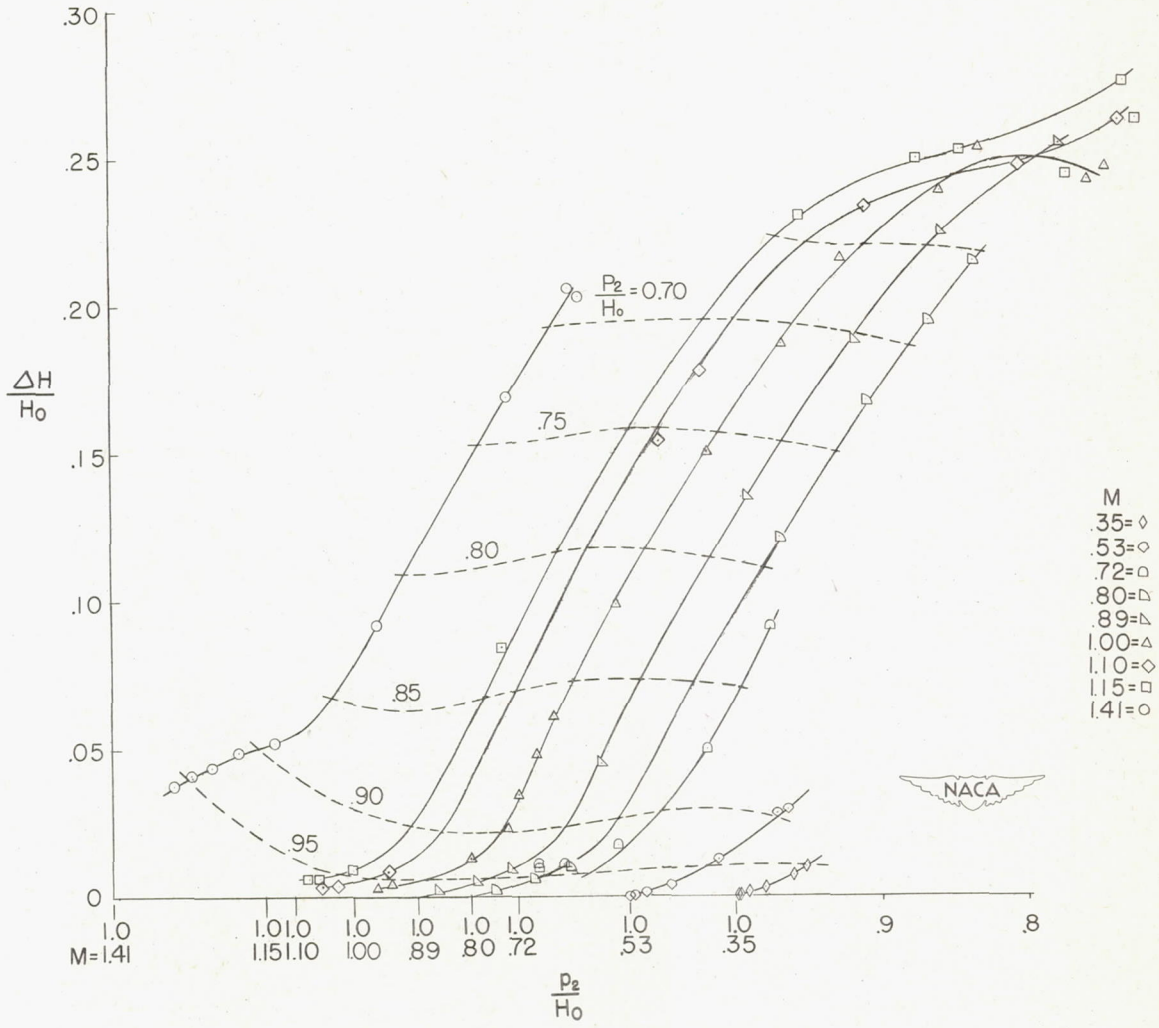
(b) Long inlets.

Figure 7.- Variation of total-pressure loss with back pressure ratio at M = 1.41.



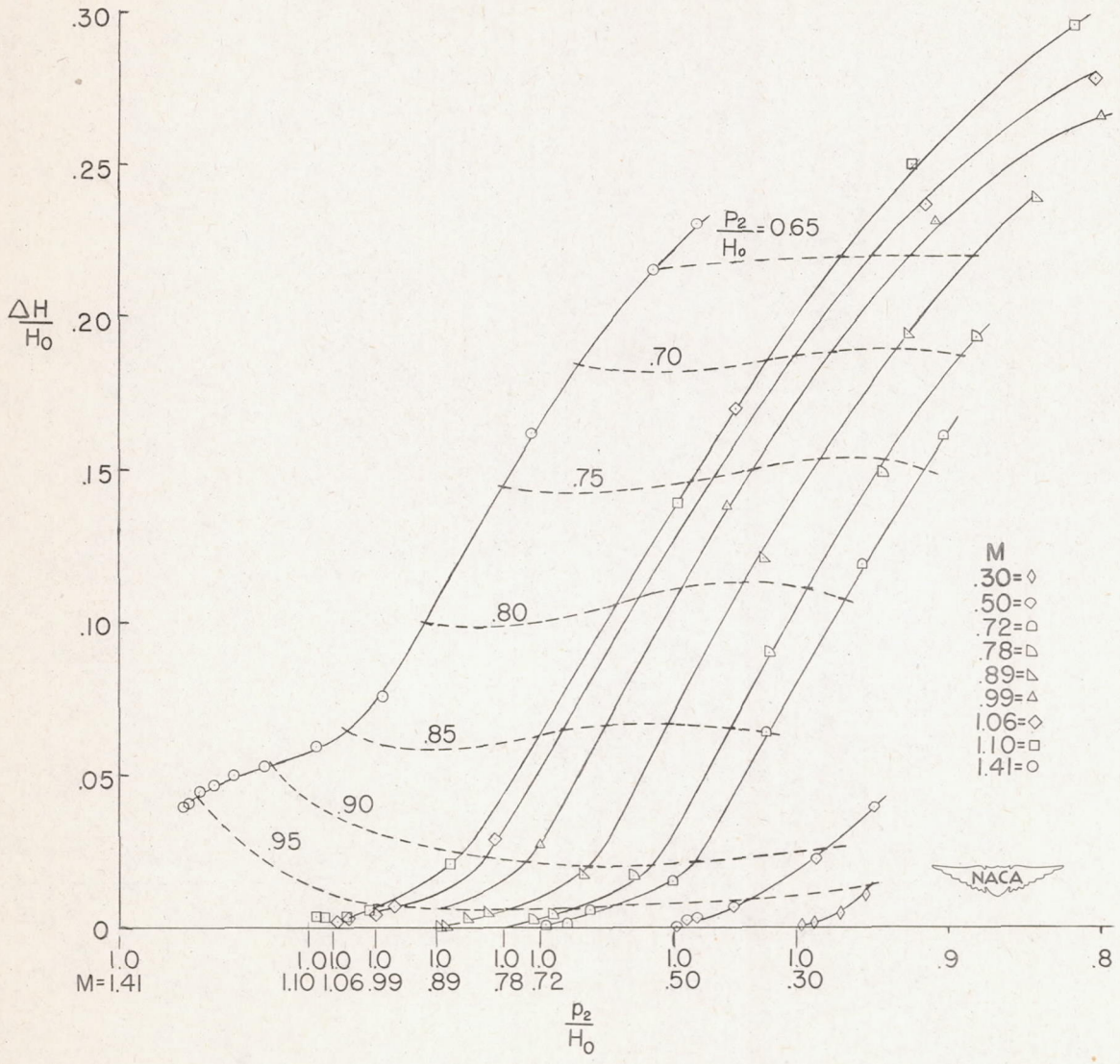
(a) Configuration I: Short symmetrical inlet.

Figure 8.- Variation of total-pressure loss with diffuser static pressure.



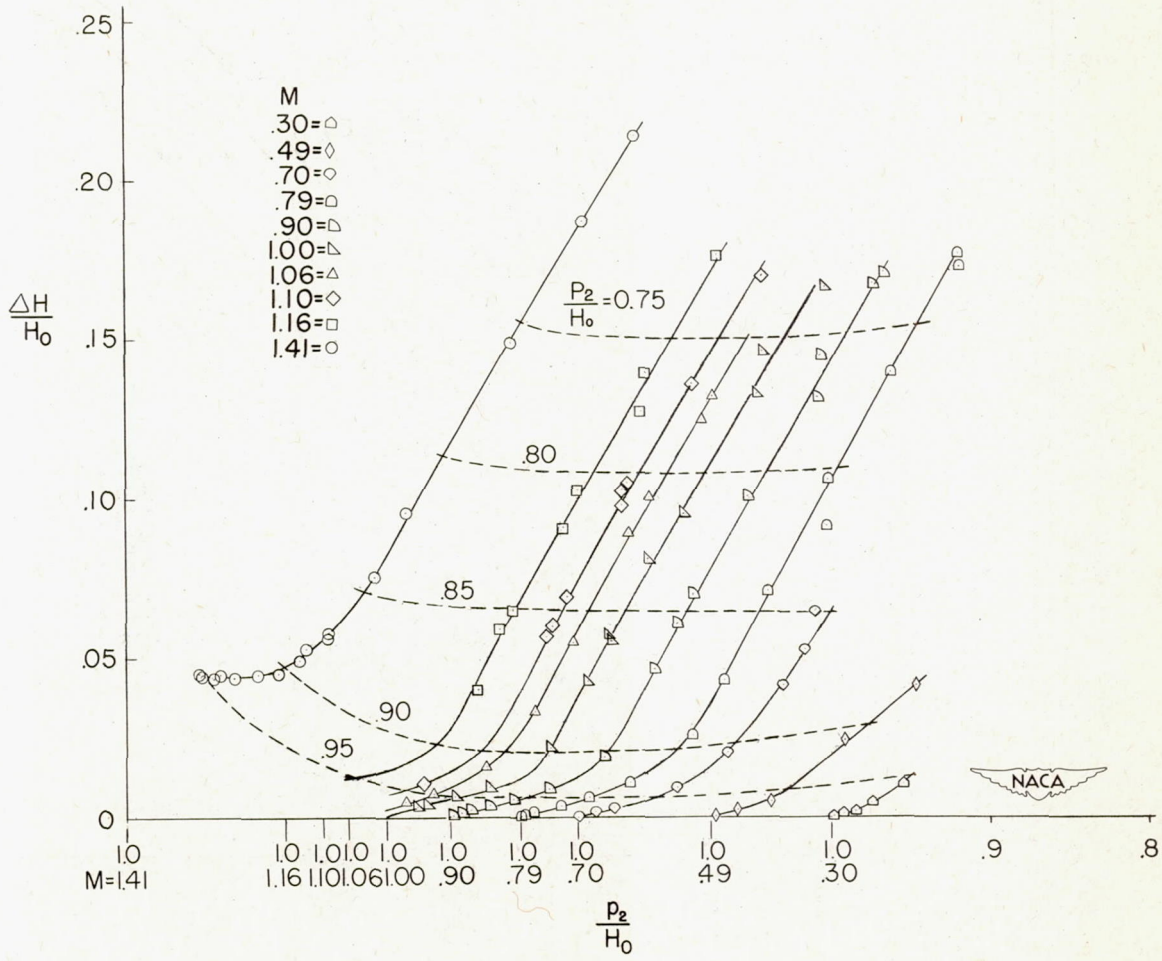
(b) Configuration II: Short inlet, 5° skew.

Figure 8.- Continued.



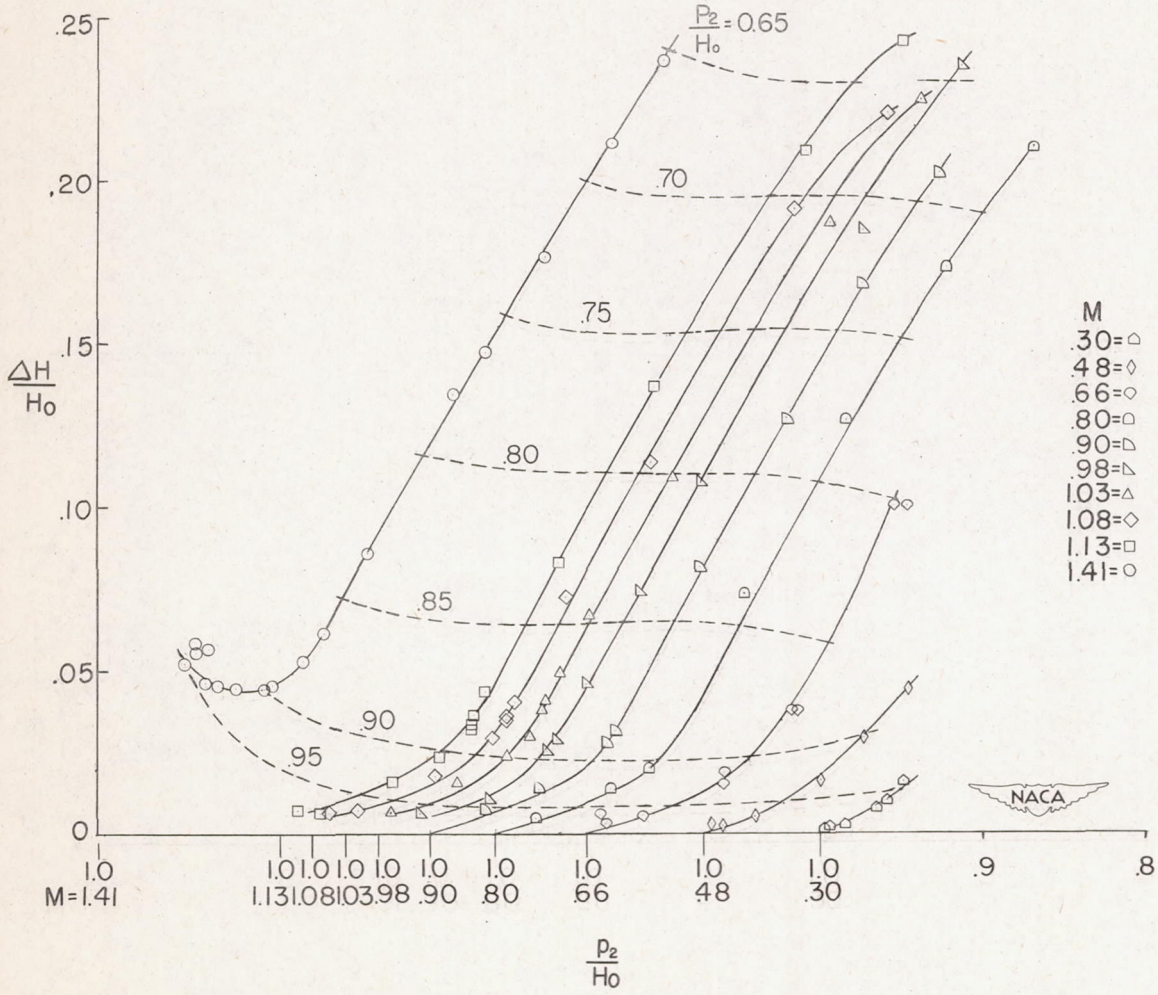
(c) Configuration III: Short inlet, 10° skew.

Figure 8.- Continued.



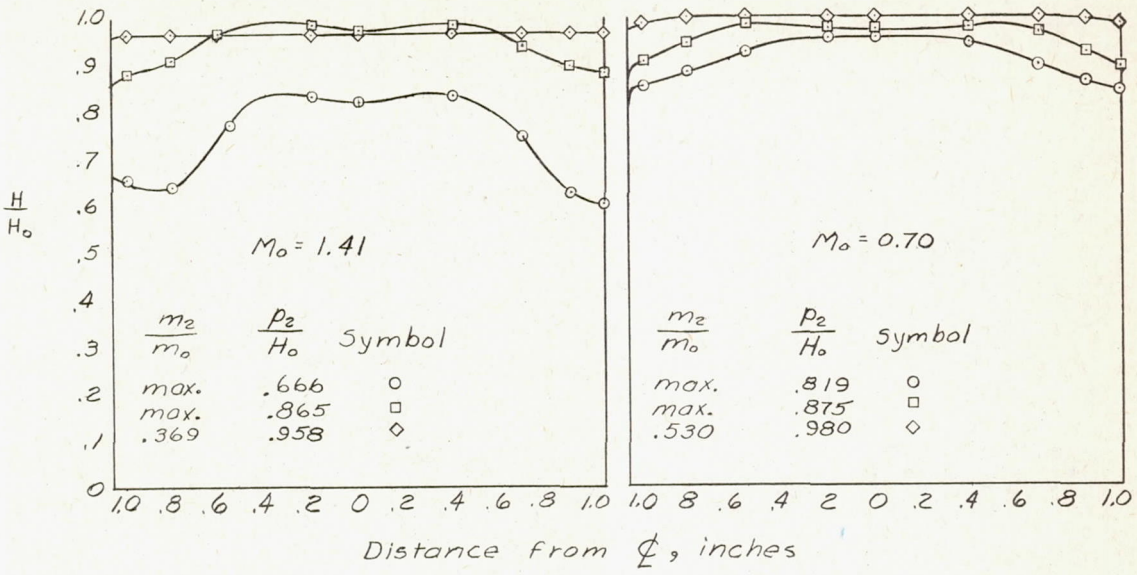
(d) Configuration IV: Long symmetrical inlet.

Figure 8.- Continued.

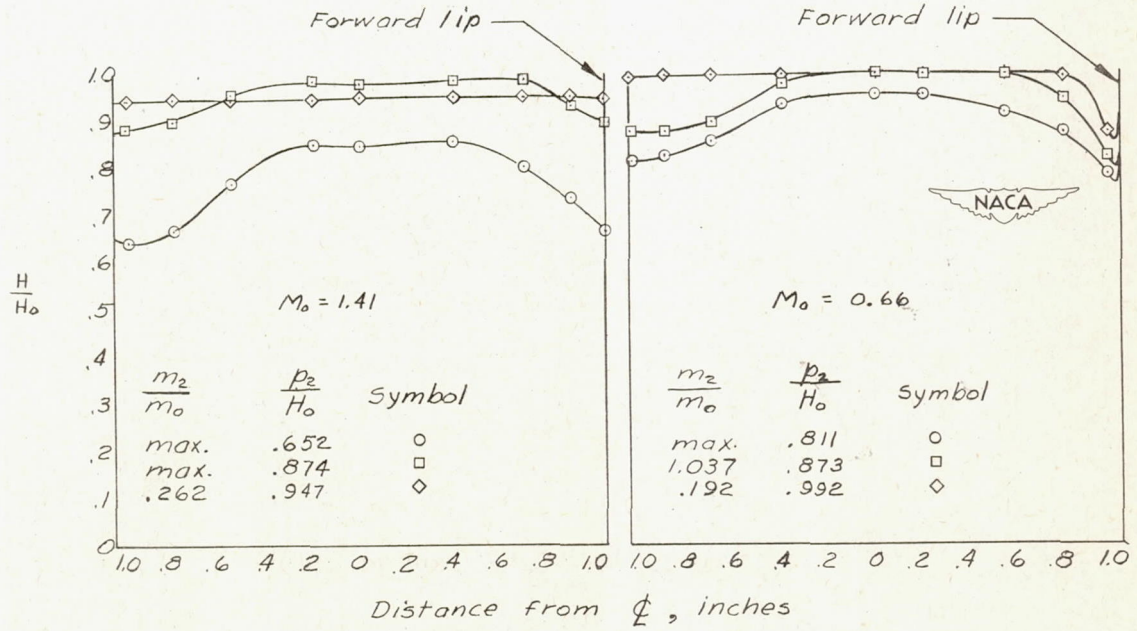


(e) Configuration V: Long inlet, 45° skew.

Figure 8.- Concluded.



(a) Configuration I: Short symmetrical inlet.



(b) Configuration V: Long inlet, 45° skew.

Figure 9.- Typical total-pressure profiles measured at the end of the diffuser.